**FLUVIAL EROSION ON MARS: IMPLICATIONS FOR PALEOCLIMATIC CHANGE;** Virginia C. Gulick and Victor R. Baker, Department of Geosciences and the Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; email address: gulick@convx1.ccit.arizona.edu.

Fluvial erosion on Mars has been nonuniform in both time and space. Viking orbiter images reveal a variety of different aged terrains exhibiting widely different degrees of erosion. Based on our terrestrial analog studies, rates of fluvial erosion associated with the formation of many of the valleys on Mars is probably on the order of hundreds of meters per million years, while rates of erosion associated with the formation of the outflow channels probably ranged from tens to hundreds of meters in several weeks to months. However, estimated rates of erosion of the Martian surface at the Viking Lander sites are extremely low, on the order of 1 μm/yr or less. At most this would result in a meter of material removed per million years, and it is unlikely that such an erosion rate would be able to produce the degree of geomorphic work required to form the fluvial features present elsewhere on the surface. In addition, single terrain units are not eroded uniformly by fluvial processes. Instead fluvial valleys, particularly in the cratered highlands, typically are situated in clusters surrounded by vast expanses of uneroded surfaces of the same apparent lithologic, structural, and hydrological setting. Clearly throughout its geologic history, Mars has experienced a nonuniformity in erosion rates. By estimating the amount of fluvial erosion on dissected terrains and by studying the spatial distribution of those locations which have experienced above normal erosion rates, it should be possible to place further constraints on Mars' paleoclimatic history.

In the heavily cratered terrains, evidence for fluvial erosion is found on the ejecta blankets of impact craters, on some volcanoes, and in intercrater plains regions. Many of the valleys in the intercrater plains appear to be associated with dark units which have been interpreted as igneous sill intrusions [1]. An asymmetric distribution of valleys around impact craters is common on Mars, unlike drainages situated around terrestrial impact craters which tends to be more uniform. While most of the Martian valley networks are attributed to formation by ground-water outflow processes [2,3,4], the distribution of these networks is unlike valley systems formed by ground-water sapping on Earth.

On Mars, valleys exhibiting a runoff-dominated morphology are rare; sapping valleys form as isolated systems. On Earth, sapping valleys almost always form with runoff dominated systems, regardless of lithologic or climatic conditions. In Hawaii, sapping valleys develop when the larger runoff valleys tap into the underlying ground-water reservoir. The addition of ground water to the fluvial system increases overall stream power and accelerates erosion at valley heads and along walls. Oversteepening of relief and removal of support for the overlying material causes subsequent collapse in these areas and results in the characteristic sapping morphology of theater-headed tributaries and either U-shaped or broad flat-floored valleys with steep walls. Sapping valleys form in a variety of climatic regimes and lithology. On the Colorado Plateau, under semi-arid conditions, sapping valleys have formed in sedimentary deposits of highly permeable, jointed sandstone which is underlain by a relatively impervious rock unit composed of mudstones, siltstones and sandstones. Runoff-dominated systems are also present and form under the same lithologic, stratigraphic, and climatic conditions as the sapping valleys; morphologic differences are attributed to structural constraints that determine the effectiveness of surface and ground-water flow [5]. In the permafrost region along the eastern North Slope of Alaska the ground is frozen to depths of several hundred meters. Here spring-fed valleys and gullies flow year-round while runoff-fed streams flow only in the warmer months. The average precipitation is only a few centimeters of snow per year [6].

The heavily cratered terrains contain numerous valley systems. We have selected two of the best developed valleys in the heavily cratered terrains for comparison with our estimates of valley erosion on martian volcanoes. A particularly well-formed drainage network is located along the highlands-lowlands boundary at 42.5°S, 92.6°. Although at first glance this valley system exhibits a high degree of integration, which led many to cite as evidence for an early warm climate on Mars, detailed study of this valley system indicates less morphological similarity to terrestrial runoff valleys than previously thought. The system lacks a hierarchial network of tributaries (see also [2]), unlike the runoff dominated systems on Earth. The estimated volume of valley erosion (assuming valley side slopes of between 10° and 30°) yields between $10^{11}$ and $10^{12}$ $m^3$ of material removed to form the valley network. The estimated eroded volume in the Parana valley system, at 22°S, 8.5° in the Margaritier Sinus region, also lies within this range. These eroded volumes are remarkably similar to those estimated for the volcanoes Alba Patera, Hecates Patera, and Ceraunius Tholus. Hadriaca and Tyrrhena Paterae have estimated eroded volumes 1 to 2 orders of magnitude larger. Results are shown in Figure 1. Assuming a particular lithologic environment, estimates of Martian valley erosion can be combined with terrestrial fluvial erosion rates scaled to the gravity of Mars in order to obtain estimates of the total volume of water required to form each set of Martian valleys. Some estimates of the ratios of water volume to eroded volume for Mars are as low as 2 or 3 to 1 [7]. Based upon our own study of fluvial erosion on volcanic landscapes, we find ratios as large as 1000 to 1. The total water volume using each estimated ratio is shown for each valley group in Figure 2. For each locality the lower bar represents the uncertainty due to valley side wall slopes while using a water to eroded volume ratio of 3:1, the upper bar using a ratio of 1000:1.

As Figure 2 indicates, while the uncertainty in absolute quantity of water required to erode these valleys is large,

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the quantity of water passing through the two selected valley systems on the heavily cratered terrain does not drastically differ from that on the martian volcanoes, barring major differences in lithology. Since the valleys on some volcanoes were formed much later than the heavily cratered terrain valleys, we conclude that the climatic controls on valley formation must have been similar for the various valleys.

Whether the formation of the martian valley networks provide unequivocal evidence for drastically different climatic conditions remains debatable. Recent theoretical climate modeling seems to preclude the existence of a temperate climate early in Mars' geological history [8], but such a climate may have been possible later when the sun's luminosity was close to today's value. An alternative hypothesis [9] suggests that Mars had a globally higher heat flow early in its geological history which would bring water tables to within 350 meters of the surface. While this would allow liquid water to exist closer to the surface and initiate circulation of subsurface water at depth, most of the valley networks would have probably required ground water to be much closer to the surface. However, the addition of persistent, vigorous, localized hydrothermal circulation such as those associated with igneous intrusions, volcano formation, and large impact craters could circulate ground water into the surface environment and may be able to initiate and maintain hydraulic gradients sufficient for valley formation. The horizontal lines in Figure 2 illustrate the cumulative discharge of hydrothermal systems associated with 50, 500, and 5000 $km^3$ igneous intrusions.

The valley characteristics discussed above suggest a scenario involving both precipitation and hydrothermal activity. Directly adjacent to the hydrothermal system, heat flow can be sufficient to entirely melt through the permafrost zone. Snow falling in the vicinity would be melted from the rising thermal energy as well. Alternatively, water vapor emitted by the hydrothermal system might produce enhanced precipitation along the perimeter of the zone. In areas away from an active hydrothermal system snowfall would not melt because of the lack of significant geothermal energy; this snow would sublimate and produce little or no significant erosion of the surface. Thus the formation of locally vigorous hydrothermal systems may explain why valley development tends to be clustered and why some fairly well developed fluvial valleys are adjacent to regions of similar age and apparently similar lithology with little to no valley development.

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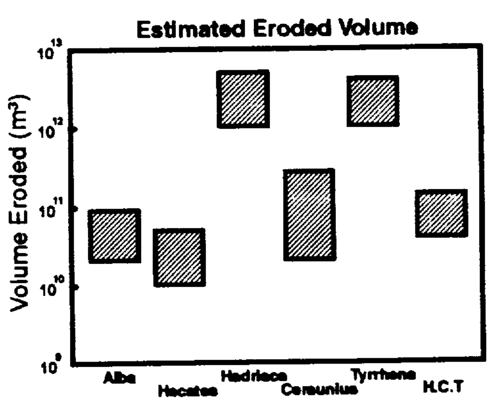


Figure 1.

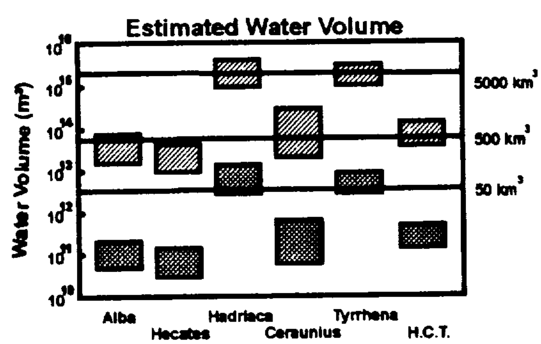


Figure 2.